

OFFSHORE RADIATION OBSERVATIONS FOR CLIMATE RESEARCH AT THE CERES OCEAN VALIDATION EXPERIMENT

A NEW “LABORATORY” FOR RETRIEVAL ALGORITHM TESTING

Charles K. Rutledge¹, Gregory L. Schuster², Thomas P. Charlock²,
Frederick M. Denn¹, William L. Smith Jr², Bryan E. Fabbri¹, James
J. Madigan Jr¹, Robert J. Knapp³,

1 Analytical Services and Materials, Inc., Hampton, VA

2 NASA Langley Research Center, Climate Sciences Branch, Hampton, VA

3 Science Applications International Corporation, Hampton, VA

Corresponding Author:

Ken Rutledge

c.k.rutledge@larc.nasa.gov

Phone: 757-827-4643 FAX: 757-825-8659

Suite 300, One Enterprise Parkway

Hampton, VA 23666

ABSTRACT

When radiometers on satellites point toward Earth with the goal of sensing an important variable quantitatively, rather than just creating a pleasing image, the task at hand is often not simple. The electromagnetic energy detected by the radiometers is a puzzle of various signals; it must be solved to quantify the specific physical variable. This task, called the retrieval or remote sensing process, is important to most satellite-based observation programs. It would be ideal to test the algorithms for retrieval processes in a sealed laboratory, where all the relevant parameters could be easily measured. The size and complexity of the Earth make this impractical. NASA's Clouds and the Earth's Radiant Energy System (CERES) project has done the next best thing by developing a long-term radiation observation site over the ocean. The relatively low and homogeneous surface albedo of the ocean make this type of site a simpler environment for observing and validating radiation parameters from satellite-based instruments. To characterize components of the planet's energy budget, CERES uses a variety of retrievals associated with several satellite-based instruments onboard NASA's Earth Observing System (EOS). A new surface observation project called the CERES Ocean Validation Experiment (COVE), operating on a rigid ocean platform, is supplying data to validate some of these instruments and retrieval products. This paper describes the ocean platform, the types of observations being performed there, and highlights of some scientific problems being addressed.

CAPSULE SENTENCE:

NASA's CERES program is performing high quality surface radiation monitoring in support of climate change research on an ocean platform off of Virginia's coast.

NASA's Clouds and the Earth's Radiant Energy System (CERES) project is observing the radiant energy leaving the Earth's atmosphere. CERES produces an archive of the radiation budget, from the bottom to the top of the atmosphere, with high temporal and spatial resolution for multiple years, with an accuracy necessary for climate change research (Wielicki et al., 1996). One expected payoff from analyzing this archive will be a new level of understanding of how clouds and aerosols affect the planet's energy budget. Climate theory indicates that the veracity of a climate model hinges strongly on the accuracy of the radiation budget simulated by the model. CERES data is a key testbed for such models. To fill the testbed with quality data, much is required.

The parameters needed to fill the CERES archive, such as irradiances at various altitudes within the atmosphere's column, are not directly measured by the CERES instruments which are presently circling the planet on several of NASA's Earth Observing System (EOS) of satellites (TRMM, TERRA, and AQUA). "Retrieval algorithms" that use the CERES measurements, ancillary data, and radiative transfer theory are required for this processing. These algorithms deal with intricacies like geo-location, viewing geometry, surface properties, sun glint, and the cloud, aerosol and gaseous constituents of the atmosphere, as well as the incomplete spatial and temporal sampling of the planet by the satellites.

Apart from the operation and calibration of the satellite instruments, developing and testing the retrieval algorithms is a large part of the CERES effort. It would be ideal to test the algorithms for retrieval processes in a sealed laboratory, where all the relevant parameters could be easily measured. The size and complexity of the Earth make this impractical. CERES instead uses a few score sites worldwide, each with surface radiometers, as a virtual laboratory. One site is over the ocean.

An ocean site offers two characteristics that are important when trying to learn the most about the atmosphere from the vantage point of a satellite. In the visible and near infrared wavelengths, constituents of the atmosphere alter the upwelling and downwelling radiation. From space, constituents (aerosols, clouds, water vapor, and molecular species)

are easiest to detect over dark surfaces with uniform reflective properties. The ocean's surface meets these criteria, and land surfaces, which are brighter and more spatially inhomogeneous, generally do not.

The CERES Ocean Validation Experiment (COVE) is a new “laboratory” for long-term radiation observations in the ocean environment that benefits from the site's surface properties. COVE is implemented on the Chesapeake Lighthouse ocean platform located in the coastal Atlantic Ocean approximately twenty-five kilometers off the Virginia, US coastline (Figure 1). The small size of the ocean platform (tens of meters) offers another favorable characteristic for an ocean observation site compared to sites on small islands (thousands of meters). The ocean platform is so small that it does not affect its local weather as happens on many small islands. Since about seventy percent of the planet is covered by water, getting the remote sensing algorithms correct over the oceans is really important.

MODELS ARE KEY The important energy quantities needed for atmospheric radiation budget research are the shortwave and longwave irradiances (see glossary). These quantify the radiant energy originating from the sun and from the Earth (plus constituents in the atmosphere). We need to know these irradiances at the top, surface, and within the atmosphere; they drive the general circulation and the hydrological cycle. Radiation can be absorbed or emitted, and it may change directions by scattering (off constituents in the atmosphere) or reflecting (off the surface). There are typically errors of 1% or more in our observations and models of vital irradiances.

The CERES instruments measure planet leaving energy as radiances in the shortwave and longwave regions of the electromagnetic spectrum at the top-of-the-atmosphere (TOA). As the EOS satellites with CERES instruments aboard them circle the planet, the radiances are sensed at multiple angles below the satellites. Angular distribution models are used to convert the radiances to irradiances. Radiative transfer models are used to estimate upwelling and downwelling irradiances at the planet's surface, at TOA, and within the atmosphere's column. Cloud retrieval models quantify the location, type and

properties of clouds in the atmosphere. The COVE was established to test components of the retrieval processes within these models.

PLATFORM DESCRIPTION The Chesapeake Lighthouse ocean platform is a rigid multi-level steel structure that was built in the mid-1960s by the US Coast Guard as an important aids-to-navigation resource. Its large pylons sink about 70 m into the sandy ocean floor, and the highest point on the structure is about 37 meters above the mean sea level. This height and stability are necessary so that accurate pointing of instruments is possible (well above the breaking wave spray that sometimes occurs when the sea is rough). Ships and buoys simply cannot offer this stability. We have implemented self-contained power and communications systems to control instrumentation and access the data products obtained at the ocean platform.

OBSERVATIONS AT COVE The quality of COVE data is enhanced by subscribing to the rigorous standards of several observation networks. Table 1 lists the networks that operate at the COVE site and also the particular instruments involved. Over five years of continuous basic radiation observations have been collected at the site (beginning in April 2000). Standard meteorological data have been collected since 1984 by NOAA's National Data Buoy Center. Time histories from the other observation networks operating at the site are not as long because they were added later. The multiple networks allow us to measure both the inputs and outputs of some of the parameters associated with the retrieval models mentioned above. Measuring the inputs and outputs allows detailed testing of the components of the retrieval processes for the radiant energy moving within the atmosphere and ocean. At times, special instrumentation and aircraft platforms have played an important part in the observations made at the COVE site (see Intensive Operations Periods box).

SURFACE IRRADIANCES The broadband radiation observations at COVE follow the Baseline Surface Radiation Network (BSRN, <http://bsrn.ethz.ch>) calibration and sampling protocols (Ohmura et al., 1998, McArthur, 2005). For the downwelling surface

irradiance, dual solar trackers are presently deployed. Pyrheliometers mounted on the solar trackers that maintain pointing toward the sun are used to obtain the direct solar irradiance. The same solar trackers provide shading mechanisms for shortwave pyranometers (for the diffuse irradiance measurement). The direct and diffuse measurements are combined to obtain the global downwelling shortwave irradiance at the surface. Dome shaded pyrgeometers measure the downwelling longwave irradiance. Figure 2A shows the location of the downwelling irradiance sensors on the tower of the ocean platform. Sensors for measuring the photosynthetically active radiation (PAR) irradiance are also located on the tower top. These instruments measure the radiation that arrive to the surface from the atmosphere. These observations have been compared to the retrieved quantities output by the radiative transfer models used by CERES (see Science Problems section).

To quantify the radiation that leaves the surface, upwelling observations of longwave irradiance (using a pyrgeometer) and shortwave irradiance (using a pyranometer) are located on a “catwalk” structure which extends 8 m from the platform structure (Figure 2B). The downwelling broadband data are archived at the BSRN archive (webpage noted above), the other irradiance data can be obtained at (<http://cove.larc.nasa.gov>) .

Measuring upwelling and downwelling shortwave spectral irradiances with shadowband radiometers resolves the spectral distribution of energy, which gives insight on how well the models are performing.

AEROSOL AND CLOUD LAYERS NASA’s Micropulse Lidar Network (MPLnet) operates a lidar at the COVE site for observations to learn about the vertical structure of clouds and aerosols in the atmosphere. Measurements of the backscattering of pulsed laser energy determines the location of aerosol and cloud particles within the atmospheric column at altitudes well above those of standard ceilometers (Welton et al., 2001). The instrument has an unobscured vertically pointing view from its position on the helicopter landing pad near the tower at COVE (Figure 2C). Profile data are available at

<http://mplnet.gsfc.nasa.gov/>. These observations provide inputs to the radiative transfer models which need information about the location of aerosols and clouds in the atmospheric column above the COVE site.

VISIBLE ATTENUATION AND SKY RADIANCES A Cimel sunphotometer operating at the COVE site is part of NASA's Aerosol Robotic Network (AERONET), a ground based network of radiometers located throughout the world (Holben et al., 1998, 2001). The sunphotometer is mounted on a programmable tracker enabling direct sun measurements as well as sky radiance measurements. This instrument system is located on top of the tower at the COVE site (Figure 2D). Direct sun measurements are used to retrieve multi-spectral aerosol optical depths and total column precipitable water when the path between the instrument and the sun is free of clouds (Bruegge et al., 1992; Smirnov et al., 2000). Sky radiance scans are input to retrieval models to infer the fundamental optical properties used to characterize the atmosphere (wavelength specific extinction optical thickness, single scattering albedo and the asymmetry factors [Dubovik and King, 2000; Dubovik et al., 2000]). These optical characteristics summarize the entire atmospheric column above the COVE site. They may be partitioned into atmospheric layers using the information retrieved by the MPLnet lidar. This combined, layered optical property information is a fundamental input required for the radiative transfer models used by CERES. The AERONET data archive available at <http://aeronet.gsfc.nasa.gov/> contains data from the COVE site since October, 1999.

WATER VAPOR AND TEMPERATURE (LAYERS) Multiple sources of information for the water vapor content and atmospheric temperature structure are available at COVE. Radiosondes are launched during intensive operation periods (IOPs) to obtain profiles of temperature and relative humidity within the atmospheric column but such IOPs are rare. We are unable to launch sondes from the site daily since it is unmanned. To find suitable profile information, we have compared COVE sonde temperature profiles to products provided by the Goddard's Earth Observing System, GEOS-4 (Bloom et al., 2005). Agreement within +/- 1 % was found for atmospheric pressures from 975 to 200 hPa (results not shown) for twenty-seven temperature profiles

observed during the month of July, 2001. Without having actual sonde data, the GEOS-4 data may be used to provide realistic column characterization for the COVE site.

NOAA's Global Systems Division Demonstration Branch (GSDDDB) operates a global positioning system (GPS) receiver at the COVE site to determine the total column precipitable water vapor (Businger et al., 1996, Duan et al., 1996). The microwave signal suffers an atmospheric time delay in its transit from a satellite to the surface, and the magnitude of the delay is dependent upon the amount of water vapor. These data are available at the NOAA GSDDDB GPS Meteorology website (<http://www.gpsmet.noaa.gov/>).

A scanning microwave radiometer (on short-term loan from the Department of Energy's Atmospheric Radiation Measurement program) was recently deployed to retrieve profiles of water vapor and liquid water content (Figure 2E). These data are available on the COVE website. These profiles are necessary inputs to radiative transfer models when the optical properties of the atmosphere need to be inferred.

OCEAN SKIN TEMPERATURE COVE operates an infrared radiation pyrometer for measuring sea surface temperature. The instrument is mounted on the tower top and points at the ocean's surface on the east side of the lighthouse (Figure 2F). The ocean skin temperature is used to verify surface longwave retrievals and longwave observations performed by CERES.

OCEAN COLOR RADIANCES Old Dominion University's Center for Coastal and Physical Oceanography performs spectral water leaving radiance observations continuously, and in-water optics observations with water samples for wet-lab analyses intermittently, since midyear 2001. These measurements are used to test coastal zone retrieval algorithms for NASA's Moderate Resolution Imaging Spectrometer (MODIS) ocean color program. NASA's AERONET program recently deployed an ocean scanning photometer (SEA Prism) which scans both the sky and ocean to retrieve the visible spectral water leaving radiances. These observations have been used for testing ocean

color satellite retrievals. The ocean color radiance instruments are located on the tower top at the COVE site (Figure 2G).

OCEAN/ATMOSPHERE REGIONAL CHARACTERIZATION We have implemented COVE at a location over the ocean to benefit from the dark and spatially homogeneous surface properties of ocean. When the surface is dark and homogeneous, the effect of surface albedo on scattered radiation is reduced, and this key input to a radiative transfer model can be specified with more confidence. This reduces the "wiggle room" of uncertainty for model inputs and allows calculated irradiances to be compared with observations at a tougher standard. But are the properties of the ocean and atmosphere at COVE similar to those of the open ocean? Some answers follow.

OCEAN COLOR A freshwater plume that often exits the mouth of the Chesapeake Bay affects many factors associated with the inner continental shelf areas of the Mid-Atlantic Bight (physical: Boicourt, 1981 Roman and Boicourt, 1999, biological: Rutledge and Marshall, 1981, Grothues and Cowen, 1999, chemical: Bates and Hansell, 1999). We've used satellite derived ocean color data to address this issue. The ocean color community classifies natural waters into two categories. In "case 1" (usually open ocean) waters, the water leaving radiances are primarily altered by chlorophyll-a and other components that naturally covary with it (other chlorophylls, zooplankton and degradation products). In "case 2" (often coastal) waters, chlorophyll, colored dissolved organic matter and sediment loads combine to modulate the water leaving radiances in a more complex way (Sathyendranath, 2000).

Clear sky chlorophyll-a retrievals from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) instrument were used to compare the ocean color of the water at the COVE site relative to nearby locations shown in Figures 3A. By assuming the water classification for the offshore Atlantic ocean location to be case 1 and the classification for the water in the middle of the Chesapeake Bay is case 2, we can characterize the COVE site relative to these locations.

The results of six years SeaWiFS retrievals (Figure 3B) suggest the COVE site's chlorophyll concentrations and hence ocean color is more similar to the bay site than the open ocean site. The bay plume appears to have an influence on the ocean color at COVE for all periods of the year. These results demonstrate the ocean color at COVE is hardly ever similar to the open ocean site (case 1). But the map (Fig. 3A) is false color. Using the on-line Coupled Ocean Atmosphere Radiative Transfer Model (COART, Jin et al., 2005) and assuming chlorophyll concentrations of 0.2 mg m^{-3} for case 1, 2 mg m^{-3} for COVE, and 5 mg m^{-3} for case 2, we calculate broadband surface albedos (solar zenith angle of 20 degrees and wind speed of 5 m sec^{-1}) of 0.032 for case 1, 0.034 for COVE, and 0.036 for case 2. All three locations have low broadband albedos.

AEROSOL CHARACTERISTICS Urban and continental aerosol size distributions are typically dominated by fine mode particles (having radii less than about 0.6 microns), while desert and maritime aerosols are typically dominated by coarse mode particles (radii greater than 0.6 microns). Although the Chesapeake Lighthouse is located 25 km from the nearest land mass, the aerosols at this location are generally dominated by small particle sizes; they are consistent with urban/continental aerosols (Figure 4).

Predominantly westerly winds cause aerosols from the North American continent to pass over COVE regularly. Our back trajectory analysis (not shown) for the 1999-2003 time period using NOAA's Hysplit model (<http://www.arl.noaa.gov/ready/hysplit4.html>) indicates that 67 percent of the one day trajectories originate over the North East United States and another 23 percent of the trajectories originate over the Southern United States.

Wintertime aerosol optical depths (AODs) at COVE typically correspond to clean conditions, with monthly averages of about 0.08 at 0.5 micron during December through February (not shown). The AOD increases throughout the Spring until it peaks at monthly averaged values of about 0.35 during the hazy summers months (June through August). The summertime peak in AOD occurs during the same time of year that the total

column precipitable water vapor peaks, indicating that hygroscopic particles play a significant role in solar attenuation for the summertime aerosols.

The seasonal variability of the atmospheric aerosols at COVE is also exhibited in the aerosol size distributions at the site. Figure 4 shows the seasonal average aerosol size distributions at the COVE site (downloaded from the AERONET database). All of the distributions are multi-modal, with a relative minimum at a radius of about 0.6 microns. The solid black line of Figure 4 corresponds to the relatively pristine conditions of the winter months (December-February), with low concentrations of both the fine and coarse modes. The spring months of March-May show an increase in both modes. The hazy summer months (June-August) have the most pronounced fine mode. These results indicate that the aerosols over the COVE site are not typical of marine environments (which are characterized by greater volumes for the coarse modes).

CLOUD CLIMATOLOGY The cloud conditions at any specific surface observation site plays an important part in altering the downwelling shortwave and longwave irradiances. We used an algorithm developed by Long and Ackerman (2000) that is based on radiation measured at the site to infer the percentage of sky (for example 0-3 percent = clear, 97-100 percent = overcast) that is obscured by clouds. Fig. 5 shows the monthly mean percent clear, overcast and partly cloudiness for the September 2000 to January 2004 time period. The annual trend for clear skies show the summer months to have the fewest periods of clear skies (June-August: approximately 10 percent), while the month of October has the highest occurrence of clear skies (35 percent). May has the highest occurrence of overcast skies, and the summer months (JJA) have the highest occurrence of partly cloudy skies (approximately 60 percent).

SCIENCE PROBLEMS FOR COVE

The site is presently well equipped for ocean/atmosphere radiation studies in clear skies. We are implementing instruments for in situ aerosol properties in 2006 to augment the existing retrievals and to provide aerosol information under cloudy skies. The aerosol in situ instrumentation suite includes:

- a condensation nuclei counter that counts all particles with diameters greater than 0.010 μm ,
- a cloud condensation nuclei counter that counts all aerosol particles capable of activating into cloud drops at supersaturations common to clouds,
- an aethelometer for measuring the aerosol absorption coefficient at seven wavelengths,
- wet and dry nephelometers for measuring wet and dry aerosol scattering at one wavelength (the combination of wet and dry scattering measurements also provide an indication of the aerosol hygroscopic growth),
- an electrical aerosol detector that provides the average diameter of accumulation mode aerosols (i.e., aerosols with diameters from 0.01 to 1 μm).

An optimal future for projects at COVE would include instrumentation to observe cloud microphysical properties and quantities. This would allow the COVE radiometry system to be applied to a wide range of complexity that the atmosphere can produce from clouds and aerosols.

Some of the clear sky issues we have addressed to date are discussed below.

CERES IRRADIANCE RETRIEVAL AT THE SURFACE How does the retrieval of surface irradiance for the ocean surface scene type at COVE compare to other scene types found on the planet? To answer this questions, we can compare retrieved CERES surface irradiances to observations at COVE and also to observations from other surface observation sites from various scene types (snow, desert, cropland, grassland, shrubland, etc.). This comparison is made possible by using the CERES ARM Validation

Experiment (CAVE, Rutan et al., 2001), a web-accessible archive of time synchronized surface observations and CERES products (<http://www-cave.larc.nasa.gov/cave/>) We have used the Terra Edition 2B Surface and Atmosphere Radiation Budget (SARB) products from CAVE for this clear sky only comparison (Charlock et al, 2005).

For each surface type, the difference distribution between the retrieved and observed surface irradiance is shown (Figure 6). The medians (center bands) of the distributions for the Water Bodies group and Crop/Natural Vegetation Mosaic group indicate the smallest differences between retrieved versus observed (their medians fall close to the 0). The largest differences are found in the Fresh Snow group and the Deciduous Broadleaf Forest group (median falls farthest from 0). The Water Bodies has the smallest dispersion and the Fresh Snow group has the largest dispersion.

The largest contrast between surface types is found when comparing the Fresh Snow group and the Water Bodies group. The retrieval over snow (which has the highest broadband albedo) is poor. Its median is farthest from the zero and its dispersion is the largest of all the groups. The retrievals over water bodies (which have the lowest albedo) shows near zero bias and the smallest dispersion. Ninety percent of the water bodies group is made up of observations from the COVE site. The existing oceanic island sites offer precious few clear sky observations that synchronize with the CERES SARB.

The low surface albedo over water surfaces permits a more accurate MODIS retrieval of AOD, which is a key input for the flux calculation. The fresh snow scene type with its high albedo results in the largest dispersion and bias of all the scene types. The snow albedo is often inhomogeneous too. If the large albedo near an observation site differs from that over the mean of the large CERES field of view, multiple scattering will cause a bias in the CERES calculation. Retrieving the necessary parameters for input into the models is more difficult over the snow scene type. Here, the ocean's low albedo appears to make the retrieved insolation more accurate. The other scene types fall in between these two groups with respect to retrieval performance.

OCEAN ALBEDO PARAMETERIZATION The COVE broadband and spectral irradiance data have been used for validation purposes in a parameterization of ocean albedo (not shown here) using the Coupled Ocean/Atmosphere Radiative Transfer (COART) model (Jin et al., 2004). This radiative transfer model accounts for a layered atmosphere and a layered ocean as a continuum of characteristic optical properties, after accounting for the change in refractive index at the surface. The parameterization was developed to allow global climate models access to a dynamic ocean albedo based on multi-year observations of albedo as a function several parameters (optical depth, solar cosine zenith, wind speed and concentrations of chlorophyll-a). The ocean albedo parameterization results may be obtained at the following website: <http://snowdog.larc.nasa.gov/jin/getocnlut.html>. These results are being used operationally by CERES to determine ocean albedo for input to the radiative transfer calculations.

SUMMARY NASA's CERES project is performing high quality ocean environment shortwave and longwave radiation observations required for climate change research on a unique radiation monitoring site located on an ocean platform. Observation methods of the BSRN are used to provide the most accurate ocean environment long-term radiation measurements available. The co-location of several observation networks at the site provide valuable information for verifying algorithms associated with radiation transfer mechanisms involving the ocean and atmosphere.

The waters surrounding the COVE site are indicative of the case 2 waters but the broadband albedo calculated for the site is not much different from case 1 (open ocean) waters. The aerosols are characteristic of continental/urban aerosols not marine aerosols. Agreement between comparisons of CERES retrieved surface shortwave irradiance to the observed shortwave parameters obtained at the COVE site show negligible bias and have the smallest variability when compared to other scene types representing the planet's

surface. Ocean albedo studies have been summarized and are now available for use in global climate models.

The anticipated value of establishing a radiation monitoring site to benefit from the low surface reflective properties of ocean is being realized at COVE. The accumulation of long term radiation observations from COVE should prove valuable for future testing of retrieval algorithms required for satellite-based instruments.

Acknowledgments Funding for the COVE project is provided through the NASA EOS program office through the CERES grant. The radiative transfer modeling efforts of Zhonghai Jin have led to many interesting validation/observation efforts and many interesting discussions on radiative transfer theory. The COVE project has benefited significantly from working with numerous members of the US Coast Guard's Group Hampton Roads. Their guidance in marine safety and assistance in the initial implementation at the site was and continues to be invaluable. We thank Brent Holben and the AERONET staff for maintaining the ocean and atmosphere observing instruments used in this investigation and for availing retrieval products associated with those observations.

REFERENCES

- Bates N. R. and D. A. Hansell, 1999: A high resolution study of surface layer hydrographic and biogeochemical properties between Chesapeake Bay and Bermuda. *Marine Chemistry*, **67**, 1–16.
- Bloom, S., A. da Silva, D. Dee, M. Bosilovich, J.-D. Chern, S. Pawson, S. Schubert, M. Sienkiewicz, I. Stajner, W.-W. Tan, M.-L. Wu, 2005: Documentation and Validation of the Goddard Earth Observing System (GEOS) Data Assimilation System - Version 4 . Technical Report Series on Global Modeling and Data Assimilation 104606 , 26. Document <http://gmao.gsfc.nasa.gov/systems/geos4/>
- Bruegge, C.J., J.E. Conel, R.O. Green, R.O. Margolis, R.G. Holm, G. Toon, 1992: Water vapor column abundance retrievals during FIFE. *J. Geophys. Res.*, **97**, 18759 - 18768.
- Boicourt, W. C., 1981: Circulation in the Chesapeake Bay entrance: estuary-shelf interactions. In *Proceedings of the Chesapeake Bay Plume Study, Superflux 1980*. NASA Conf. Publication 2188, 61-78.
- Businger, S., S.R. Chiswell, M. Bevis, J. Duan, R. Anthes, C. Rocken, R.W. Ware, M. Exner, T. VanHove, F.S. Solheim, 1996: The promise of GPS in atmospheric monitoring, *Bull. Amer. Meteor. Soc.*, **77**.
- Castanho, A. D. A., J. Vanderlei Martins, P. Artaxo, L. Remer, M. Yamasoe, 2005: Chemical characterization of aerosols on the East Coast of the United States using aircraft and ground based stations during the CLAMS Experiment. *J of Atmos. Sci.*, **62**, 934-946 .
- Charlock, T. P., and T. L. Alberta, 1996: The CERES/ARM/GEWEX Experiment (CAGEX) for the retrieval of radiative fluxes with satellite data. *Bull. Amer. Meteor. Soc.*, **77**, 2673-2683.
- Charlock, T. P., F. G. Rose, D. A. Rutan, L. H. Coleman, T. Caldwell, and S. Zentz, 2005: Global Multiyear Analysis of CERES Terra Observations and Radiative Transfer Calculations. Proceedings of ARM Science Team Meeting, 14-18 March 2005, Daytona Beach. Available at www.arm.gov under “Publications”.
- Charlock, T. P., F. G. Rose, D. A. Rutan, C. K. Rutledge, K. T. Larman, Y. Hu, S. Kato, and M. Haeffelin, 2000: Clouds and the Earth’s Radiant Energy System Calibration Document / Surface and Atmospheric Radiation Budget Validation Plan for CERES Subsystem 5.0 (Compute Surface and Atmospheric Fluxes), http://asd-www.larc.nasa.gov/validation/ceresval_r4.0_ss5.0.pdf
- Chowdhary, J., B. Cairns, M. I. Mishchenko, P. V. Hobbs, G. Cota, J. Redemann, K. Rutledge, B. N. Holben, and E. Russel, 2005: Retrieval of aerosol scattering and absorption properties from photo-polarimetric observations over the ocean during the CLAMS experiment. *J of Atmos. Sci.*, **62**, 1093-1117.

- Duan, J., M. Bevis, P. Fang, Y. Bock, S. Chiswell, S. Businger, C. Rocken, F. Solheim, T. van Hove, R. Ware, S. McClusky, T.A. Herring, R.W. King, 1996: GPS Meteorology: Direct estimation of the absolute value of precipitable water. *J. Appl. Meteor.*, **35**, 830-838.
- Dubovik, O. and M. D. King, 2000: A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements. *J. Geophys. Res.*, **105**, 20673-20696.
- Dubovik, O., A. Smirnov, B. N. Holben, M. D. King, Y.J. Kaufman, T. F. Eck, and I. Slutsker, 2000: Accuracy assessments of aerosol optical properties retrieved from AERONET sun and sky-radiance measurements. *J. Geophys. Res.*, **105**, 9791-9806.
- Fu, Q., and K.-N. Liou, 1993: Parameterization of the radiative properties of cirrus clouds. *J. Atmos. Sci.*, **50**, 2008-2025.
- Gatabe, C. K., M. D. King, A. I. Lyapustin, G. T. Arnold, and J. Redemann, 2005: Airborne spectral measurements of ocean directional reflectance. *J of Atmos. Sci.*, **62**, 1072-1092.
- Grothues T. M. and R. K. Cowen, 1999: Larval fish assemblages and water mass history in a major faunal transition zone. *Continental Shelf Research*, **19**, 1171-1198.
- Holben, B. N., T. F. Eck, I. Slutsker, D. Tanré, J. P. Buis, A. Setzer, E. Vermote, J. A. Reagan, Y. Kaufman, T. Nakajima, F. Lavenue, I. Jankowiak, and A. Smirnov, 1998: AERONET- A federated instrument network and data archive for aerosol characterization. *Rem.Sens.Environ.*, **66**, 1-16.
- Holben, B.N. and D. Tanre and A. Smirnov and T.F. Eck and I. Slutsker and N. Abuhassan and W.W. Newcomb and J.S. Schafer and B. Chatenet and F. Lavenue and Y.J. Kaufman and J. Vande Castle and A. Setzer and B. Markham and D. Clark and R. Frouin and R. Halthore and A. Karneli and N.T. O'Neill and C. Pietras and R.T. Pinker and K. Voss and G. Zibordi, 2001: An emerging ground-based aerosol climatology: {A}erosol optical depth from {AERONET}. *J. Geophys. Res.*, **106**, D11, 12067-12097.
- Ignatov, A., P. Minnis, N. Loeb, B. Wielicki, W. Miller, S. Sun-Mack, D. Tanre, L. Remer, I. Laszlo, and E. Geier, 2005: Two MODIS aerosol products over ocean on the Terra and Aqua CERES SSF datasets. *J of Atmos. Sci.*, **62**, 1008-1031.
- Jin, Z., T. P. Charlock, W. L. Smith Jr., K. Rutledge, 2004,: A parameterization of ocean surface albedo. *Geophys. Res. Ltrs.*, **31**, 2004, 4 pp.

- Jin, Z., T. P. Charlock, W. L. Smith, Jr., K. Rutledge, G. Cota, R. Kahn, J. Redemann, T. Zhang, D. A. Rutan, F. Rose, and B. N. Holben, 2005: Radiation measurement and model simulation for the CLAMS experiment. *J of Atmos. Sci.*, **62**, 1053-1071.
- Kahn, R., W.-H. Li, J. Martonchik, C. Bruegge, D. J. Diner, B. Gaitely, W. Abou, O. Dubovik, B. Holben, A. Smirnov, Z. Jin and D. Clark, 2005: MISR calibration and implications for low-light-level aerosol retrieval over dark water. *J of Atmos. Sci.*, **62**, 1032-1052.
- Levy, R. C., L. A. Remer, J. V. Martins, Y. J. Kaufman, A. Plana-Fattori, J. Redemann, and B. Wenny, 2005: Evaluation of the MODIS aerosol retrievals over ocean and land during CLAMS. *J of Atmos. Sci.*, **62**, 947-973.
- Long, C.N., and T.P. Ackerman, 2000: Identification of clear skies from broadband pyranometer measurements and calculation of downwelling shortwave cloud effects. *J. Geophys. Res.*, **105**, 15,609 –15,626, 2000
- Magi, B.I., P.V. Hobbs, T.W. Kirchstetter, T. Novakov, D. A. Hegg, S. Gao, J. Redemann, and Beat Schmid, 2005: Aerosol Properties and Chemical Apportionment of Aerosol Optical Depth at Locations off the United States East Coast in July and August 2000. *J of Atmos. Sci.*, **62**, 919-933.
- McArthur L.J.B., 2005: Baseline Surface Radiation Network (BSRN). Operations Manual. *WMO/TD-No. 1274*, WCRP/WMO.
- Ohmura A., H. Gilgen, H Hegner, G. Muller, M. Wild, E. Dutton, B. Forgan, C. Frolich, R. Philipona, A. Heimo, G. Konig-Langlo, B. McArthur, R. Pinker, C. Whitlock, K., and K. Dehne, 1998: Baseline Surface Radiation Network (BSRN/WRMC), a new precision radiometryfor climate research. *Bull. Amer. Meteor. Soc.*, **79**, 2115-2136.
- Payne, R.E., 1972: Albedo of the Sea Surface. *J. of the Atmos. Sci.*, **29**, 959-970.
- Redemann, J., B. Schmid, J. A. Eilers, R. Kahn, R. C. Levy, P. B. Russell, J. M. Livingston, P. V. Hobbs, W. L. Smith Jr., B. N. Holben, 2005: Suborbital measurements of spectral aerosol optical depth and its variability at sub-satellite-grid scales in support of CLAMS. *J. Atmos. Sci.*, **62**, 993-1007.
- Remer, L. A., Y. J. Kaufman, D. Tanre, S. Mattoo, D. A. Chu, J. V. Martins, R.-R. Li, C. Ichoku, R. D. Levy, R. G. Kleidman, T. F. Eck, E. Vermote, and B. N. Holben, 2005: The MODIS aerosol algorithm, products, and validation. *J. Atmos. Sci.*, **62**, 947-973.
- Roman, M. R., and W. C. Boicourt, 1999: Dispersion and Recruitment of Crab Larvae in the Chesapeake Bay Plume: Physical and Biological Controls. *Estuaries*, **22**, pp. 563–574.

- Rutan, D. A., F. G. Rose, N. Smith, and T. P. Charlock, 2001: Validation Data Set for CERES Surface and Atmospheric Radiation Budget (SARB). GEWEX News, Vol. 11, No. 1 (February), pp. 11-12. Available at www.gewex.com under "Newsletter".
- Rutledge, C. K. and H.G. Marshall, 1981: Use of ordination and classification procedures to evaluate phytoplankton communities during Superflux II, *In Proceedings of the Chesapeake Bay Plume Study, Superflux 1980*. NASA Conf. Publication 2188, 469-490.
- Sathyendranath, S. (ed.), 2000: Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Waters, IOCCG Report Number 3.
- Smirnov, A., B.N. Holben, T.F. Eck, O. Dubovik, I. Slutsker, 2000: Cloud screening and quality control algorithms for the AERONET database, *Rem. Sens. Env.*, **73**, 337-349.
- Smith, W. L. Jr., T.P. Charlock, R. Kahn, J.V. Martins, L.A. Remer, P.V. Hobbs, J. Redemann, C.K. Rutledge, 2005: EOS-TERRA aerosol and radiative flux validation: An overview of the Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS) experiment. *J of Atmos. Sci.*, **62**, 903-918.
- Smith, W. L. Sr., D. K. Zhou, A. M. Larar, S. A. Mango, H. B. Howell, R. O. Knuteson, H. E. Revercomb, and W. L. Smith Jr., 2005: The NPOESS airborne sounding testbed interferometer remotely sensed surface and atmospheric conditions during CLAMS. *J of Atmos. Sci.*, **62**, 1118-1134.
- Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, B. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's radiant energy system (CERES): an earth observing system experiment, *Bull Amer. Meteor. Soc.*, **77**, 853-868.
- Welton, E.J., J.R. Campbell, J.D. Spinhirne, V.S. Scott, 2001: Global monitoring of clouds and aerosols using a network of micro-pulse lidar systems, in *Lidar Remote Sensing for Industry and Environmental Monitoring*, U. N. Singh, T. Itabe, N. Sugimoto, (eds.), Proc. SPIE, 4153, 151-158.

Table 1: List of current geophysical measurements at the Chesapeake Lighthouse (see glossary for definitions).

Measurement	Domain ¹	Instrument	Wavelengths (μm)	Network ²	COVE Dataset
Passive Radiation Measurements					
Direct shortwave irradiance	A	Pyrheliometer	0.2-4	BSRN	Y
Diffuse shortwave irradiance	A	Pyranometer	0.2-4	BSRN	Y
Global shortwave irradiance	AO	Pyranometer	0.2-4	BSRN	Y
Longwave irradiance	AO	Pyrgeometer	5-50	BSRN	Y
PAR irradiance	AO		0.4-0.7		Y
Global and diffuse narrowband irradiance	AO	UVMFRSR	0.300-0.368 (7 bands)		Y
Global and diffuse narrowband irradiance	AO	MFRSR	0.415-0.936 (6 bands)		Y
Narrowband radiance	AO	Spectrophotometer	0.355-1.025 (17 bands)		Y
Direct and diffuse narrowband radiance	AO	Sunphotometer	0.340-1.020 (7 bands)	AERONET	N
Microwave Radiometer	A	MWR	multiple		Y
Active Radiation Measurements					
Aerosol backscatter and extinction profiles	A	Lidar	0.523	MPLnet	N
Total column precipitable water vapor	A	GPS		GPS-MET	N
Aerosol In Situ Measurements					
Number density	A	Condensation Nuclei Counter			Y
Potential Cloud Nuclei	A	Cloud Condensation Nuclei Counter			Y
Aerosol absorption coefficient	A	Aethalometer	0.37, 0.47, 0.52, 0.59, 0.88, 0.95		Y
Aerosol extinction coefficient	A	Nephelometer	0.53		Y
Average aerosol diameter	A	Electrical Aerosol Detector			Y

1. A – Atmosphere, O – Ocean, AO – Atmosphere & Ocean

2. BSRN – Baseline Surface Radiation Network; AERONET – Aerosol Robotics Network; GPS-MET – Ground-Based Meteorology;

NDBC – National Data Buoy Center; NOAA – National Oceanic and Atmospheric Administration, observations with no network association are NASA Langley projects

Glossary

Radiant Energy

Radiance	Radiant energy confined to a solid angle or cone. The angular measure to define the cones uses steradians. Radiance units are energy per area per time per frequency and per steradian (for example, $\text{W/m}^2/\text{nm}/\text{sr}$, recall $\text{W} = \text{joules sec}^{-1}$). The collection cone is oriented in space so radiance observations are always associated with a direction.
Irradiance	Radiant energy incident upon a surface. Irradiance units are energy per time and per area (for example, W/m^2). Atmospheric sensors view an entire hemisphere (2π sr).

Spectral Regions

Shortwave	Wavelengths containing energy emitted by the sun (sometimes called solar wavelengths). This spectral region spans wavelengths from 0.2-4 microns.
Longwave	Wavelengths containing energy emitted at terrestrial temperatures (sometimes called infrared thermal wavelengths). This spectral region spans wavelengths from 5-50 microns.
Broadband	Radiation measurements over the entire shortwave or longwave spectral regions.
Narrowband	Radiation measurements over a discrete spectral range of wavelengths, for example from 0.50 to 0.55 microns.
PAR	Photosynthetically-active radiation; the spectral region from 0.4 - 0.7 microns, this range includes wavelengths efficiently absorbed by various types of chlorophylls found in plants and phytoplankton.

Field of View

Global	Irradiance measurement, hemispheric field of view, includes direct and diffuse components.
Direct	Irradiance measurement of solar beam typically limited to 5 degree field of view.
Diffuse	Irradiance measurement with an instrument shaded from the direct solar beam (hemispheric field of view).

Instruments

Pyranometer	Irradiance measurement of shortwave energy.
Pyrgeometer	Irradiance measurement of longwave energy.
Pyrheliometer	Irradiance measurement of direct component of the solar energy.
Pyrometer	Radiance measurement of longwave energy.
MFRSR	Multifilter Rotating Shadowband Radiometer; shaded and unshaded narrowband irradiance measurements.
Sunphotometer	Direct narrowband radiance measurements at multiple wavelengths.

INTENSIVE OBSERVATION PERIODS box

CHESAPEAKE LIGHTHOUSE AND AIRCRAFT MEASUREMENTS FOR SATELLITES

(CLAMS). The CLAMS field campaign was conducted in summer 2001 to validate aerosol and radiation products derived from the Moderate Spectral Imaging Spectrometer (MODIS), Multiangle Imaging SpectroRadiometer (MISR), and CERES instrument data taken from the EOS Terra spacecraft (Smith Jr. et al., 2005). The synergy of a comprehensive field campaign with multi-spectral imagery (MODIS), a multi-angle sensor (MISR), and broadband accuracy (CERES) on a single spacecraft provides unprecedented data for diagnosing particular aspects of aerosol radiative forcing (i.e., Jin et al., 2005, Levy et al., 2005, Remer et al., 2005, Ignatov et al., 2005), which is a critical uncertainty factor in decadal scale climate change.

The aircraft deployment around COVE during CLAMS included the MODIS airborne simulator (Gatebe et al., 2005) and AirMISR (Kahn et al., 2005) on the ER-2 at 20 km; a interferometer in the high resolution thermal infrared on the experimental Proteus for sensing temperature, humidity, and aerosol effects (Smith Sr. et al., 2005); the Ames Airborne Sunphotometer (AATS-14) remotely sensed spectral aerosol optical depth (Redemann et al., 2005) and in situ measurements of aerosol physical (Magi et al., 2005) and chemical (Castanho et al., 2005) properties on a CV-580 at various altitudes; broadband pyranometers on a low level OV-10 (Smith Jr et al., 2005); and a photopolarimeter on a Cessna (Chowdhary et al., 2005). The ocean surface is the most ubiquitous boundary condition for solar photons approaching the earth-atmosphere system, and both the brief CLAMS campaign and the continuous COVE platform provide a rigorous testbed for the remote sensing of aerosols and fluxes with Terra over

that boundary condition. CLAMS data can be obtained from the NASA Langley Atmospheric Sciences Data Center (<http://eosweb.larc.nasa.gov>).

AIRS BALTIMORE BOMEM ATMOSPHERIC EMITTED RADIANCE INTERFEROMETER (BBAERI) OCEAN VALIDATION EXPERIMENT. The AIRS BBAERI Ocean Validation Experiment (ABOVE) was conducted by the University of Maryland Baltimore County during the summers of 2002 and 2003. In situ measurements were deployed at Chesapeake Lighthouse for validation of the AIRS instrument on the NASA EOS Aqua satellite. The instrument suite included the BBAERI, Elastic Lidar Facility, radiosondes, ozonesondes, carbon monoxide and ozone gas samplers. In addition to Aqua validation, ABOVE measurements are being used for atmospheric pollution and transport process studies. Information on the ABOVE project can be found at <http://physics.umbc.edu/~mcmillan> .

FIGURE CAPTIONS

Figure 1. The COVE site (lat:36.905N, lon:75.713W) is located in the Atlantic coastal ocean due east of Virginia's border. The ocean platform serves as an aid-to-navigation facility marking an important southern entry shipping channel to the mouth of the Chesapeake Bay. Many of our instruments are located on the light room roof on the tower part of the ocean platform (blue structure on right side in the photo). A helicopter landing pad (approximately 27m X 27m) serves as a roof for the housing section of the lighthouse. Helicopters are used for transportation of personnel and small loads for safety reasons. We use boats only for transporting large loads of supplies or instruments. The ocean's depth close to the platform is only about 12 m.

Figure 2. Locations of functional groups of sensors located at COVE (number of instruments per group): A) instruments for observing downwelling irradiances view the entire sky hemisphere, some have optical domes or windows which are cleaned daily by an automated washing system, shortwave broadband, longwave broadband, VISIBLE/UV spectral and PAR; B) instruments for observing upwelling irradiances view the entire ocean hemisphere, a problem exists because some of the "view" includes the legs of the platform and shadows from the platform contaminate the data before solar noon each day (these data are excluded from analyses), shortwave broadband, longwave broadband, VISIBLE spectral; C) aerosol and cloud backscatter lidar, requires an environmentally controlled enclosure that maintains a set temperature to within +/- 1 degree C (24 hrs/day, 365 days/year) so that the optical components in its telescope do not expand or contract (and void the calibration); D) optical extinction and radiance sunphotometers, a calibration site on Mauna Loa HI is used to cycle instruments through or an instrument calibrated at Mauna Loa is brought to the instruments (AERONET); E) scanning microwave radiometer measures directional temperatures to produce altitude-dependent profiles of water vapor (using a model); F) radiances of a portion of the longwave spectrum determines the skin temperature of the ocean's surface; G) radiometers sense radiances at the ocean's surface to determine the water leaving radiances at various narrowband wavelength intervals.

Figure 3A) Typical clear-sky chlorophyll-a retrieval (false color) from the SEAWIFS instrument aboard the SeaStar spacecraft for a region that is centered over COVE. To assess the optical classification of waters at the COVE site, an arbitrary site beyond the Gulf Stream waters off the

North Carolina coast and a site in the middle of the lower Chesapeake bay were chosen for representing Case 1 and Case 2 waters (respectively).

3B) Summary of six years of clear sky retrievals of chlorophyll-a concentrations (mg/m^3) retrieved by the SEAWIFS sensor for three sites. For most of the year, the COVE site chlorophyll-a is comparable to the bay site (Case 2) but distinct chlorophyll concentration groups emerge during summer months. These ocean color data suggests the water surrounding the COVE site should be classified as having the Case 2 water type.

Figure 4. Seasonal averages of aerosol volume distributions derived from AERONET observations made at the COVE site. X-axis (r) radius of aerosol particles (microns). Y-axis mean volume of aerosol particles ($dV/d\ln r$). Averages were taken from 41 months of level 2 data (October 1999 to February 2005, inclusive). The fine mode variation is correlated with changes in the precipitable water (PW) within the atmospheric column; summer (JJA) has the highest precipitable water concentration, winter (DJF) has the lowest precipitable water concentration.

Figure 5. Monthly cloud coverage (based on Long and Ackerman, 2000) derived from radiation observations made at the COVE site. Clear, partly cloudy, and overcast conditions are based upon 15-minute radiation observations. Daytime only.

Figure 6. Box and whiskers plots indicating distributions of differences between surface observations and CERES SARB estimates of downwelling shortwave global radiation at the surface for nine surface scene types under clear skies. Data were included if 1.) the cloud imager and the Long & Ackerman cloud index reported 0% clouds, 2.) the percentage of the scene type was greater than 50% in the CERES instrument field of view, and 3.) the sun glint angle was between 30 and 80 degrees. For retrieving the surface irradiances, CERES uses a modified version (Rose and Charlock, 2002) of the Fu-Liou (1993) radiative transfer model. Inputs to the radiative transfer model include: aerosols and cloud properties from MODIS aboard Terra, gridded fields of temperature, humidity, wind (GEOS 4, Bloom et al., 2005), ozone from NCEP Stratospheric Monitoring group Ozone Blended Analysis.

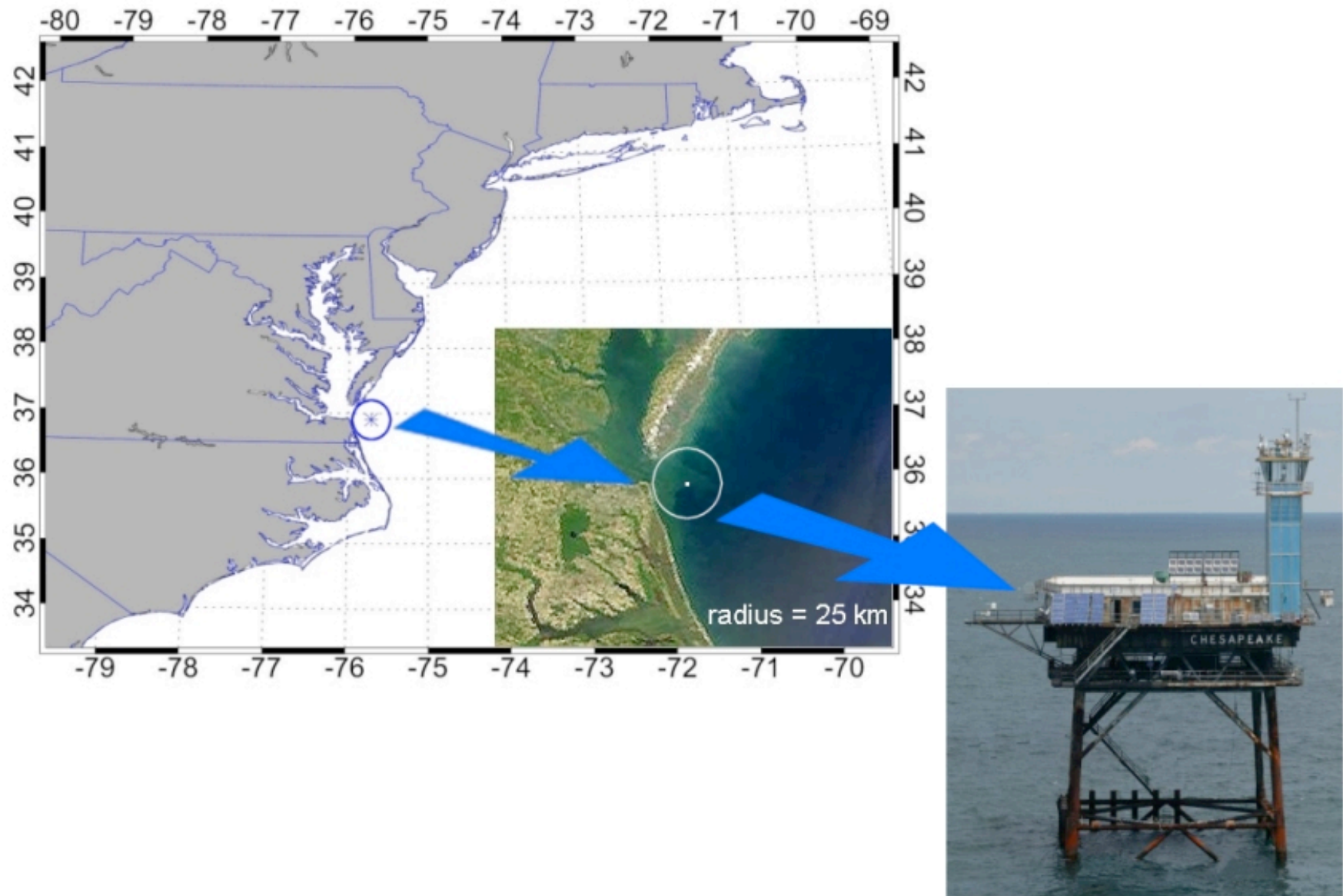


Figure 1

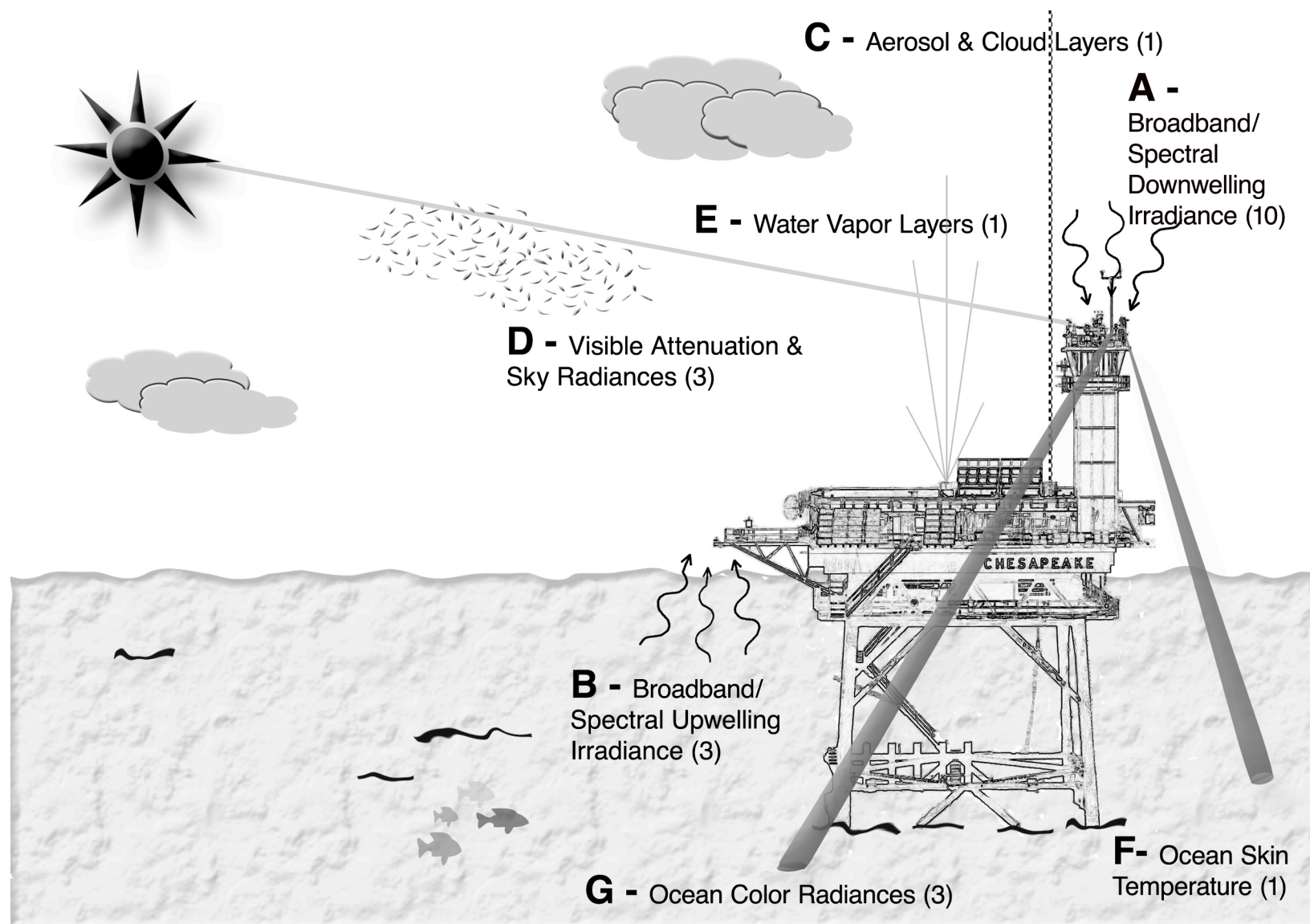


Figure 2

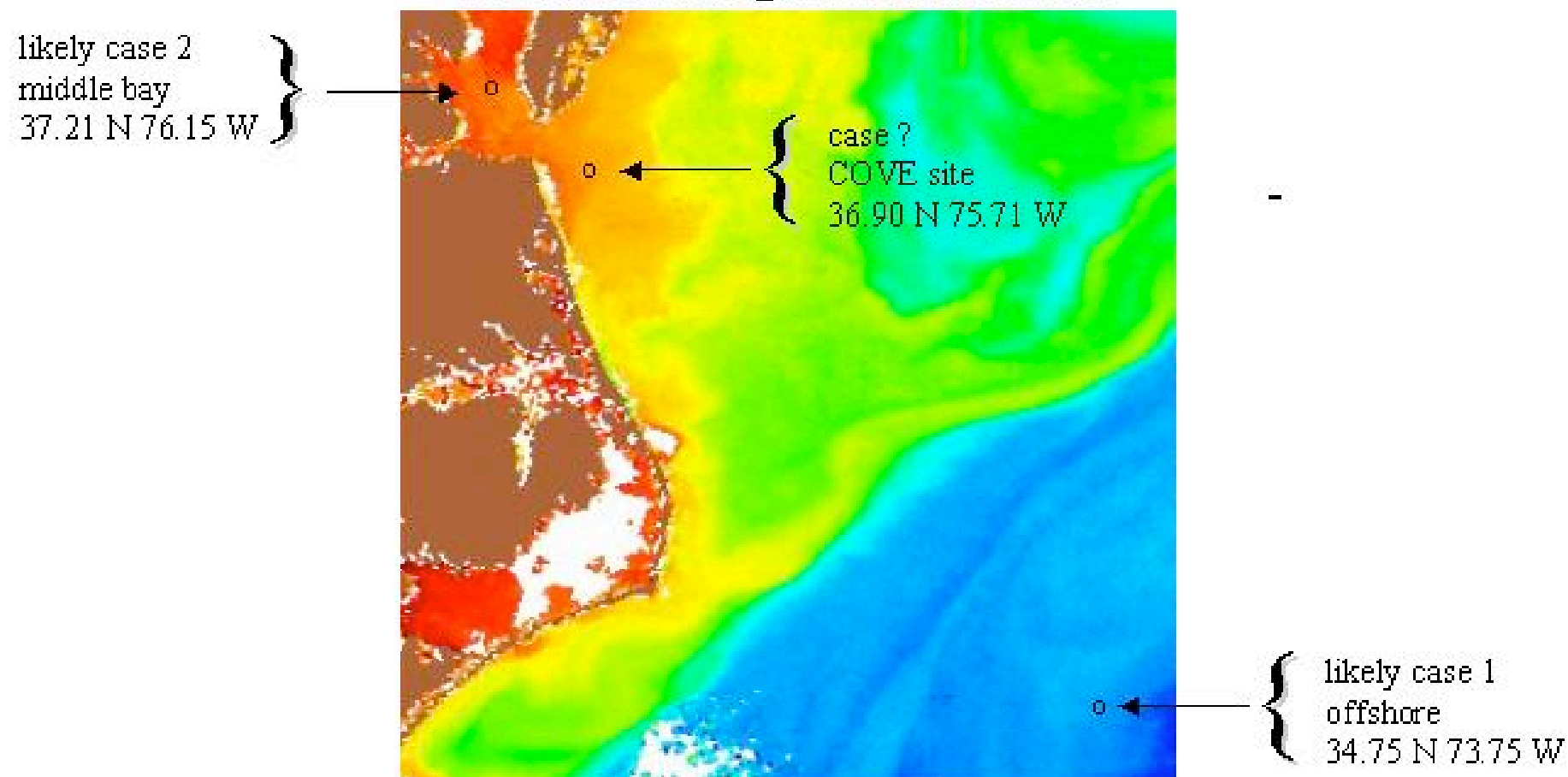


Figure 3A

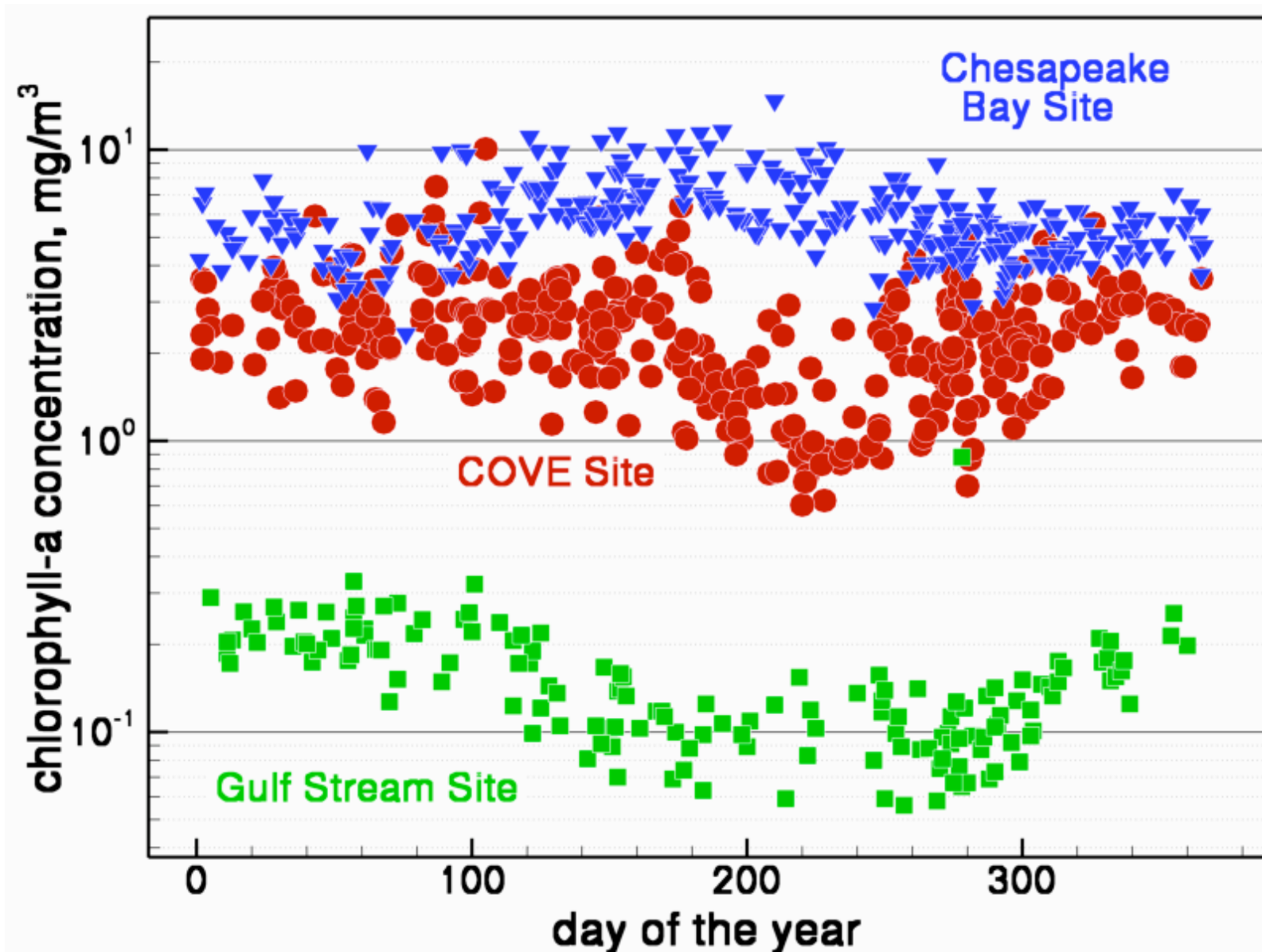


Figure 3B

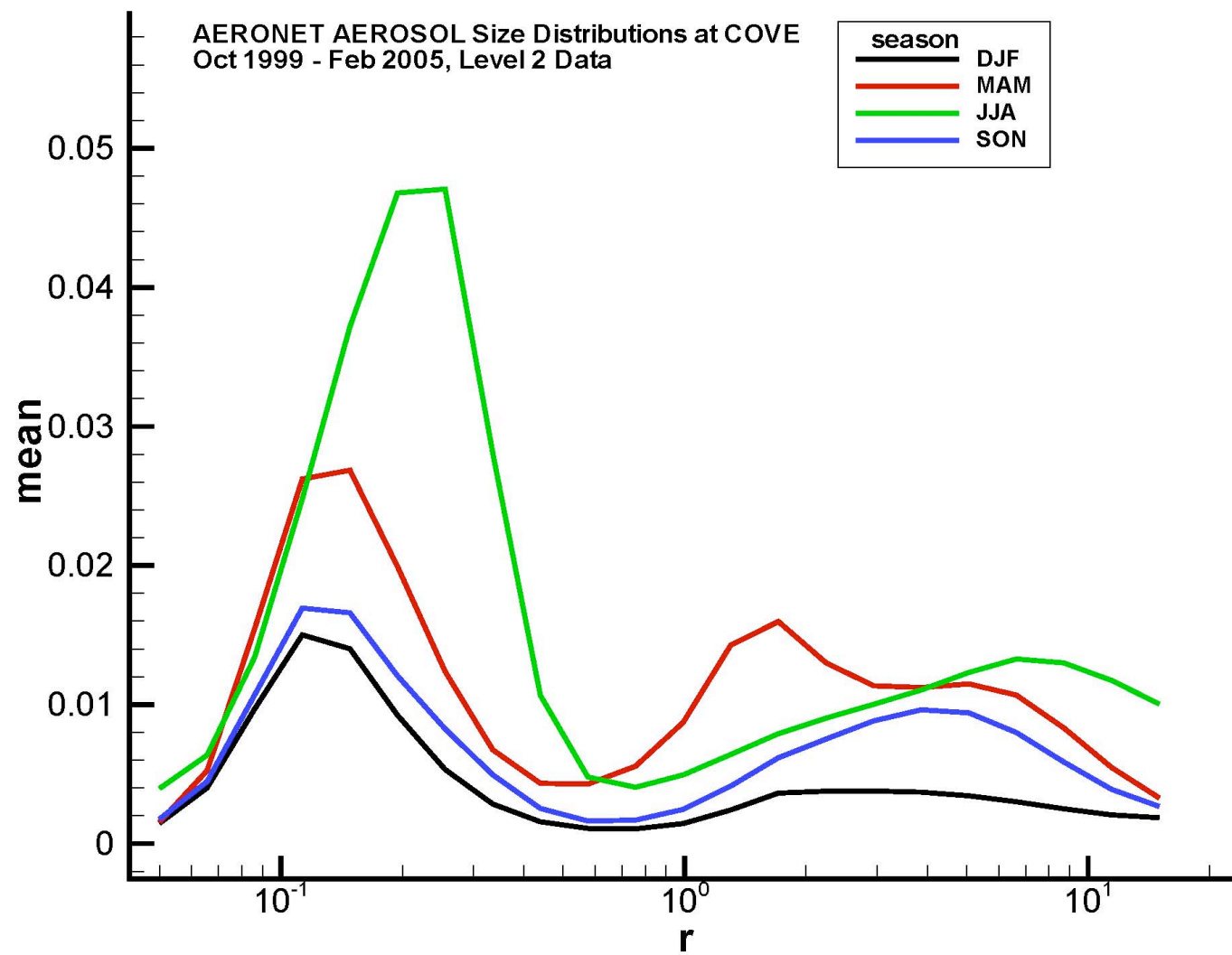


Figure 4

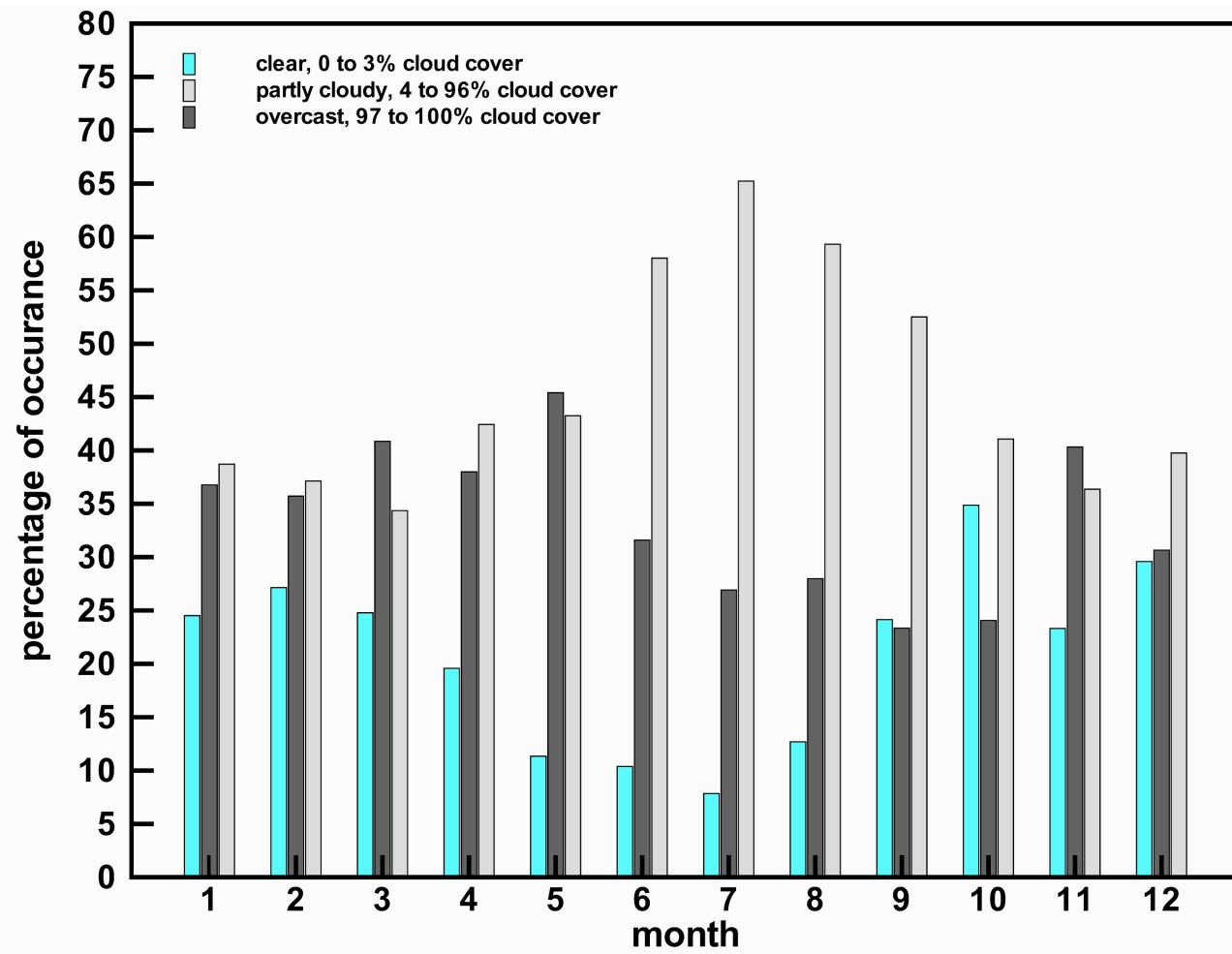


Figure 5

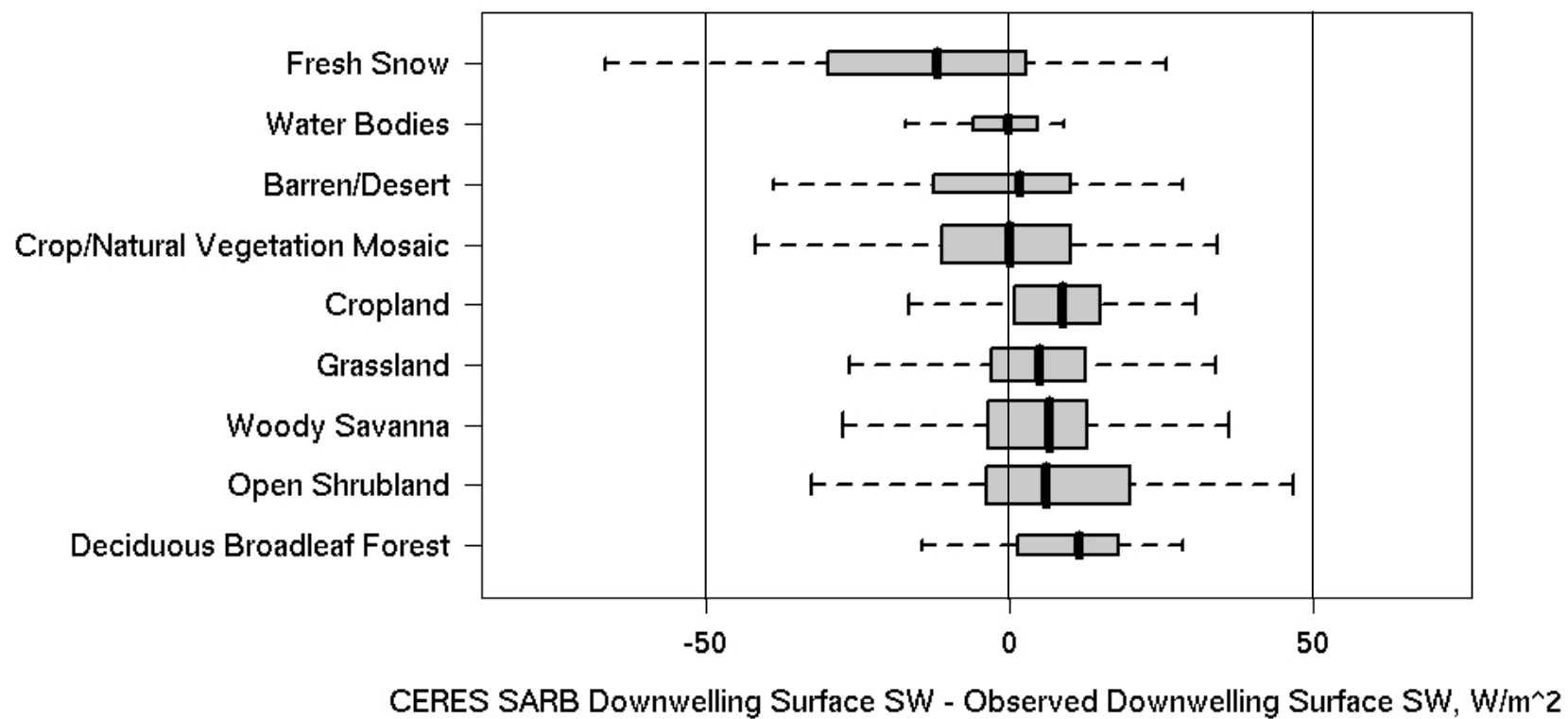


figure 6